

# The Starburst Intensity Limit And Its Ultraviolet Implications

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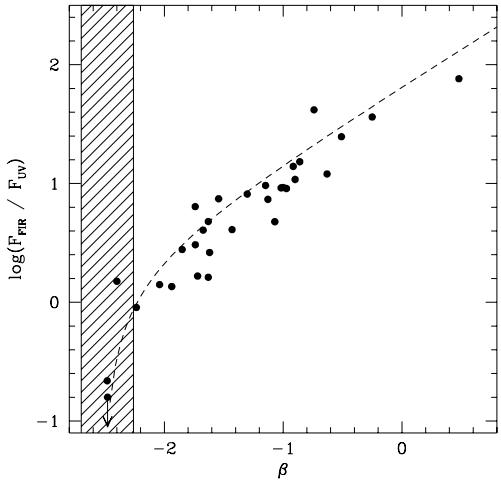
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**Abstract.** Our recent work on starbursts, particularly in the ultraviolet (UV), is summarized. The intrinsic UV fluxes of UV selected starbursts can be derived from UV data alone because, to first order, their dust behaves like a foreground screen. This allows a comparison of the bolometric effective surface brightness  $S_e$  of UV selected starbursts to other starburst samples. Starbursts have a robust (90th percentile) upper limit  $S_e \lesssim 2.0 \times 10^{11} L_\odot \text{ kpc}^{-2}$ , which strongly suggest that their global star formation intensities are regulated. The mechanism(s) involved in the regulation are not yet clear. The dust attenuation corrections for high- $z$  starbursts are significant. Calculations of the rate of evolution in the early universe based on zero dust interpretations are probably underestimated by about an order of magnitude. Hence the early universe was not quiescent, but obscured.

## INTRODUCTION

The pace of cosmic evolution is marked out by the condensation of stars from the ISM. Starbursts, regions of intense massive star formation which can dominate the bolometric output of galaxies, are crucial to our understanding of this evolution at all redshifts. In the local universe about 25% of high mass star formation is contained within starburst galaxies (Heckman, 1997; Gallego *et al.* 1995). At high redshift ( $z > 2$ ), starbursts are the easiest galaxies to detect, and can be used to directly trace the rate of evolution (Madau *et al.* 1996). So, to understand the cosmological pace of evolution, we must understand starbursts. We would like to know how to derive intrinsic star formation rates and the physics that determines these rates. Can the starburst “knob” be cranked up to arbitrary levels or is its amplitude limited?

Recently we imaged a small sample of starbursts in the ultraviolet (UV) using the HST (Meurer *et al.* 1995; hereafter M95). The basic UV structure of a starburst consists of prominent compact star clusters embedded in a more diffuse cloud. In the nearest starbursts the diffuse light starts to resolve into stars, hence star formation within starbursts occurs in both clustered and diffuse modes. In M95 we



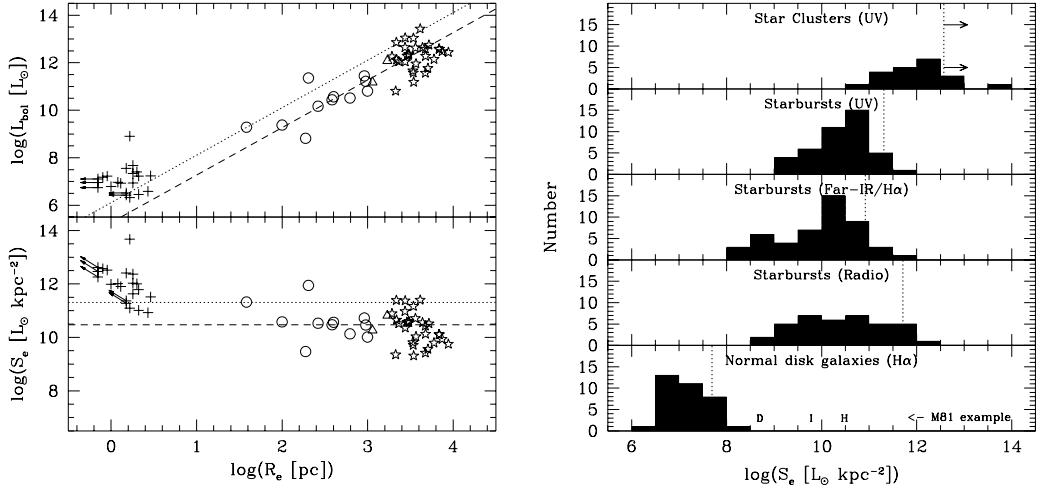
**Figure 1.** The ratio of far infrared to UV fluxes compared to UV spectral slope  $\beta$  (flux density  $f_\lambda \propto \lambda^\beta$ ) which is equivalent to a UV color. The data correspond to UV-selected starbursts. The fluxes are measured in the FIR by IRAS and in the UV ( $\lambda \approx 2300\text{\AA}$ ) by HST or IUE. The hatched region shows the expected  $\beta$  for naked ionizing populations. The dashed line shows the expected relationship for a starburst having an intrinsic  $\beta_0 = -2.5$  behind a foreground screen of dust obeying the Calzetti *et al.* (1994) attenuation law.

compared the effective surface brightness,  $S_e$  (the surface brightness within the radius containing half the total emission), of starbursts and concluded that there is an upper limit to  $S_e$ . This suggests that the intensity of starbursts is limited. Lehnert and Heckman (1996) found a similar surface brightness limit in their combined FIR/H $\alpha$  study. This prompted our more comprehensive investigation of starburst surface brightnesses (Meurer *et al.* 1997; hereafter M97) which we report on here.

## ATTENUATION AND REDDENING DUE TO DUST

Vacuum-UV imaging is indispensable for understanding starbursts since it allows the direct detection of the hot-high mass stars that power starbursts. In contrast other tracers of high-mass stars, such as H $\alpha$  (and other emission lines), radio continuum, and far-infrared (FIR) emission originate in the ISM and only indirectly trace star formation. Dust presents the biggest obstacle to understanding UV observations, since dust extinction and scattering are strongest in the UV resulting in a net attenuation of the UV flux. Fortunately, our work has proven that UV observations can reveal essential properties of high mass star formation, even in the presence of modest amounts of dust.

We are saved because dust is not a sink for photons; the absorbed radiation is reemitted thermally in the FIR. Hence the ratio of FIR to UV fluxes is an indication of net attenuation. Figure 1 shows a positive correlation between UV spectral slope  $\beta$  and  $\log(F_{\text{FIR}}/F_{\text{UV}})$  for a sample of strongly star forming galaxies as indicated by their strong recombination emission line spectra. *A priori* we expect their UV spectra to be that of an ionizing population, and hence to have an intrinsic color in the hatched region of the plot. This correlation is readily understood in terms of a simple foreground screen dust geometry, as shown by the model line. Although the dust distribution, in exact detail, may not be a *homogeneous* foreground screen,



**Figure 2** (left). Bolometric luminosity  $L_{\text{bol}}$  and effective surface brightness  $S_e$  plotted against effective radius  $R_e$  for UV-selected starbursts and star clusters. The dotted and dashed lines are the 90th and 50th  $S_e$  percentiles for the starbursts. The circles corresponds to local starbursts ( $D < 75$  Mpc), triangles to starbursts at  $z = 0.4$ , stars to high redshift ( $2.2 < z < 3.5$ ) starbursts, and crosses to clusters within starbursts having  $D < 10$  Mpc.

**Figure 3** (right).  $S_e$  distributions for star clusters (from Fig. 2), UV selected starbursts (from Fig. 2), FIR selected starbursts measured in the FIR and  $\text{H}\alpha$ , FIR selected starbursts observed at 21cm, and normal disk galaxies observed at  $\text{H}\alpha$  (see M97 for sample details). The dotted lines show the 90th percentiles of the distributions. In the bottom panel we show preliminary  $S_e$  measurements of an UV ( $\lambda \approx 1500\text{\AA}$ ) image of M81 at obtained with the UIT (Hill *et al.* 1992).

and other quantities may be involved in the correlation, this is largely unimportant for determining the attenuation correction. So long as the FIR emission results from dust reradiating the light absorbed in the UV and optical, any model that reproduces the correlation in Fig. 1 will recover the UV flux of ionizing populations to within a factor of  $\sim 3$  (corresponding to the spread in  $\log(F_{\text{FIR}}/F_{\text{UV}})$ ).

## THE STARBURST INTENSITY LIMIT

The evidence for a starburst intensity limit is summarized in Figs 2 and 3. In Fig. 2 we show measurements of our rest frame UV sample after dust attenuation correction as outlined above. For comparison with the other samples, shown in Fig. 3, luminosities and surface brightnesses are converted to bolometric units following the models of Leitherer & Heckman (1995). Note that the shape of the low  $S_e$  end of the distributions in Fig. 3 are determined by (largely arbitrary) selection effects. However there is no selection against high surface brightness. The three starburst  $S_e$  distributions have 90th percentile upper limits within a factor of three of  $S_{\text{lim}} \approx 2 \times 10^{11} L_{\odot} \text{ kpc}^{-2}$ , which we call the starburst intensity limit. This limit is very robust, applying to starbursts with  $R_e \sim 0.1$  to 10 kpc, to both local star-

bursts, and systems out to redshift  $z \sim 3$ , to both UV/optically selected starbursts and FIR selected starbursts, and to observations obtained in the UV, H $\alpha$ , FIR, and radio continuum. The lack of a strong  $\lambda$  effect, indicates that it corresponds to a limit on star formation intensity rather than being an opacity effect, and is further vindication of the UV attenuation estimates. This limit strongly indicates that the global intensity of star formation is regulated within starbursts.

In M97 we explored two physical mechanisms that may be responsible for the intensity limit: galactic winds (Heckman *et al.* 1990), and gravitational stability of the inner disk (following Kennicutt, 1989). Although we find evidence that the intensity limit is related to both mechanisms, neither predicts the value of the intensity limit, nor its robustness. Hence *determining the physics of the starburst intensity remains a major theoretical challenge*.

Although robust, this limit does not hold for all star forming scales. In particular it does not hold for the star clusters embedded within starbursts. These are small  $R_e \lesssim 10$  pc (M95) and can have  $S_e$  two orders of magnitude or more intense than  $S_{\text{lim}}$ . This is not a contradiction because  $S_{\text{lim}}$  refers to a global quantity dominated by diffuse light, whereas individual clusters usually do not dominate the total luminosity of starbursts.

Star formation in normal disk galaxies is typically three orders of magnitude less intense than in starbursts, as seen in Fig. 3. However, this may largely reflect the different star formation patterns. Typically star formation fills the central regions of starburst galaxies, whereas in normal galaxies it usually consists of H II regions, often arranged in spiral arms or rings, but otherwise fairly isolated. We illustrate how large a difference covering factor can make in the bottom panel of Fig. 3 using a UIT UV image of M81 (Hill *et al.* 1992). Its disk averaged  $S_e$ , marked “D”, is the surface brightness within the elliptical aperture containing half the UV light (the same technique used to measure the  $S_e(\text{H}\alpha)$  values shown in the bottom panel). The *isophotal*  $S_e$ , marked “I”, is the surface brightness within the isophote containing half the total flux (in other words, pixels having this or higher surface brightness comprise half the total UV flux). In effect, this value does not include any of the “empty space” between H II regions. The  $S_e$  of one of M81’s brightest H II regions is marked “H”. This comparison suggests that star formation in normal galaxies, averaged over only the actively star forming regions, may occur with the same intensity distribution as starbursts. More measurements of normal galaxies are needed to test this hypothesis.

## IMPLICATIONS

Our results have far reaching implications. We demonstrated that intrinsic UV fluxes of starbursts can be recovered from UV data alone (Fig. 1). This confirms the importance of UV observations to the study of extragalactic high mass star formation. The dust attenuation corrections are significant in the UV. The median  $\beta = -1.1$  of our UV sample corresponds to an attenuation factor of  $\sim 8$  at  $\lambda \approx$

2300Å and  $\sim 15$  at  $\lambda = 1600$  Å. The latter value corresponds to the rest  $\lambda$  of the Lyman drop out galaxies observed at high redshift (Madau *et al.* 1996). These have properties (including  $\beta$ ) consistent with those of local UV selected starbursts. Madau *et al.* (1996) use the UV luminosity density of these systems to infer that the universe was fairly quiescent (low star formation rate density, or equivalently metal production rate) at redshift  $z \approx 3$ . However they applied no dust extinction corrections. After applying our UV attenuation corrections, and adopting the same cosmology as Madau *et al.* ( $H_0 = 50$  km s $^{-1}$  Mpc $^{-1}$ ,  $q_0 = 0.5$ ) we find a lower limit of  $\sim 3 \times 10^{-3}$  M $_{\odot}$  yr $^{-1}$  Mpc $^{-1}$  for the metal production rate at  $z \approx 3$ . This is about six times higher than their estimate of the Hubble time averaged metal production rate. We find that rather than being quiescent we are observing an active but moderately obscured early universe.

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